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OVERVIEW OF THE CUMULUS HUMILIS AEROSOL PROCESSING STUDY (CHAPS)

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ABSTRACT

The primary goal of the Cumulus Humilis Aerosol Processing Study (CHAPS) was to characterize and contrast freshly emitted aerosols below, above, and within fields of cumuli, and to study changes to the cloud microphysical structure within these same cloud fields. The CHAPS is one of very few studies that have had an Aerosol Mass Spectrometer (AMS) sampling downstream of a counter-flow virtual impactor (CVI) inlet on an aircraft, allowing the examination of the chemical composition of the nucleated aerosols within the cumuli. The results of the campaign will be used to investigate differences in below-cloud and above-cloud aerosol optical, chemical, and cloud nucleating properties downwind of Oklahoma City, Oklahoma, relative to aerosols in the background regional air. Three instrument platforms were employed during the CHAPS, including the U. S. Department of Energy Gulfstream-1 aircraft, which was equipped for *in situ* sampling of aerosol optical and chemical properties; the NASA-Langley King Air B200, which carried the downward looking NASA Langley High Spectral Resolution Lidar (HSRL) to measure profiles of aerosol backscatter, extinction, and depolarization between the King Air and the surface; and a surface site equipped for continuous *in situ* measurements of aerosol properties, profiles of aerosol backscatter and meteorological conditions including total sky cover and thermodynamic profiles of the atmosphere. In spite of record precipitation over central Oklahoma, a total of eight research flights were made, including several flights near Oklahoma City, and special satellite verification flights timed to coincide with NASA satellite A-Train overpasses.

Capsule Summary:

During the summer of 2007, the CHAPS was conducted to investigate changes in the aerosol chemical and optical properties as they pass through fields of shallow cumuli.

INTRODUCTION

Aerosols directly influence climate through scattering and absorption of radiation, and indirectly through their influence on cloud microphysical and dynamic properties. The Intergovernmental Panel on Climate Change (IPCC) concluded that the global radiative forcing due to aerosols is large and in general cools the planet (Forster et al. 2007). But the uncertainties in these estimates are large due to our poor understanding of many of the important processes related to aerosols and clouds. To address this uncertainty, Ghan and Schwartz (2007) proposed an integrated strategy for addressing issues related to aerosols and aerosol processes. Using this conceptual framework, the Cumulus Humilis Aerosol Processing Study (CHAPS) is a Stage 1 activity, that is, a detailed process study examining how the characteristics of aerosols change with passage through shallow cumuli. The specific focus of the CHAPS was to provide concurrent observations of the chemical composition of the activated and non-activated aerosols, the scattering/extinction fields and detailed aerosol and droplet size spectrum in the vicinity of Oklahoma City, Oklahoma during June of 2007.

Numerous major campaigns have examined aerosol properties downwind from large pollution sources, including the Megacity Initiative: Local and Global Research Observations (MILAGRO) campaign (Molina et al. 2008) and the three Aerosol Characterization Experiments (ACE-1, ACE-2, and ACE-3) described by Bates et al. (1998), Raes et al. (2000), and Huebert et al. (2003), respectively. However these campaigns were generally focused on clear, rather than, cloudy conditions. Other studies conducted near cities have examined changes in both aerosols and clouds downwind of urban areas. For example, Alkezweeny et al. (1993) found that wintertime stratiform clouds associated with the urban plumes of Denver Colorado and Kansas City Missouri have a larger number of droplets and smaller median volume diameter than clouds that had not been affected by the urban plume. Another link between urban aerosols and clouds was suggested at the end of the last decade when Rosenfeld (1999) noted that smaller cloud droplets have smaller coalescence efficiencies, resulting in reduced precipitation and longer cloud lifetimes, providing yet another possible link to urban aerosols and climate. Recently, the New England Air Quality Study (NEAQS), and the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) 2004, which were conducted during the summer of 2004, examined the transport of pollutants and aerosols eastward from New England over the Atlantic Ocean. The Texas Air Quality Study/Gulf of Mexico Atmospheric Composition and Climate Study (TexAQS/GoMACCS) also looked at relationships between clouds and aerosols in dirty conditions around Houston, Texas (e.g. Sorooshian et al. 2007, Lu et al. 2008). In contrast to these recent studies near large or very dirty cities, the CHAPS was conducted near a moderately sized city that is representative of a large number of cities around the United States.

The CHAPS was also one of the first times that an Aerodyne Aerosol Mass Spectrometer (AMS) was used in conjunction with a Counterflow Virtual Impactor (CVI) inlet on an aircraft. The AMS provides information on the nonrefractory composition of aerosols within several large categories, while the CVI uses a counterflow relative to the main incoming airstream to exclude small droplets and unnucliated aerosols from the inlet, allowing only larger cloud droplets to enter the inlet. While a similar configuration has been used on a number of occasions on mountaintops, the only other time, to our knowledge, this method has been used on an aircraft was by a team of scientists from Environment Canada during the ICARTT 2004 campaign (Hayden et al. 2008). The combination of the CVI and AMS allow the examination of the chemical composition of the dried aerosol kernel from the cloud droplets from an airborne platform.

EXPERIMENTAL GOALS

A key objective of the U.S. Department of Energy's (DOE) Atmospheric Sciences Program (ASP: http://www.asp.bnl.gov/) is to improve the understanding of aerosol radiative effects on climate. This objective encompasses not only clear sky observations, but also studies relating the effects of both aerosols on clouds and of clouds on aerosols, in particular, how clouds affect the chemical and optical properties of aerosols. The later was the science driver in the design of the CHAPS.

The measurement strategy for the CHAPS was intended to provide measurements relevant to four questions associated with the aerosol radiative forcing issues of interest to the ASP:

1. How do the below-cloud and above-cloud aerosol optical and cloud nucleating properties downwind of a typical North American city differ from the optical and nucleating properties of aerosols in air unperturbed by urban emissions? What are the differences in the radiative properties, chemical composition, hygroscopic properties, and size distributions below and above, upwind and downwind of such a city?

2. How does the distribution of aerosol extinction vary in relation to the proximity to individual clouds and fields of clouds and why?
3. What are the differences between activated aerosols within the urban plume, and those outside the urban plume? What are the differences between aerosols that have not been activated within and outside the urban plume?
4. To what extent can large-scale models with state of the art cloud parameterizations capture the statistical features of the below-above cloud aerosols?

The material in this article presents preliminary results from the CHAPS illustrating the observations and discussing their relevancy to the questions listed above. The CHAPS is rich set of observations is available to others in the community who are interested in this topic of research.

EXPERIMENTAL APPROACH

The CHAPS consisted of a sampling strategy closely linking the DOE G-1, the NASA B200 aircraft and primary and secondary surface sites. The G-1 made *in situ* measurements of aerosol concentrations, composition, aerosol and cloud droplet size distributions, optical properties, cloud nucleating properties below, within and above clouds downwind of Oklahoma City, while the HSRL on the B200 provided remotely observed profiles of aerosol extinction, backscatter, and depolarization over the same air space as that being sampled by the G-1. Observations of boundary-layer aerosols and meteorological conditions were made at the primary surface site just north of Oklahoma

City and sky cover was measured at a nearby secondary surface site. Both of the surface sites were under the airspace in which observations were made by the two aircraft.

The *in situ* aircraft sampling strategy consisted of cross-wind legs made below, within, and above fields of fair-weather clouds (FWC). The lengths of these transects were designed to provide statistics against which to test the fidelity of parameterizations used in large-scale models describing aerosol transport over distances typical of GCM grid cells (e.g. Berg and Stull 2002). By centering the campaign in the region close to Oklahoma City, the G-1 was able to make transects that intersected an urban plume. By extending the transects on either side of the Oklahoma City plume, or by flying upwind of the city *in situ* sampling was made in air that was influenced by both local emissions and in air that was characteristic of the regional scale pollutant loading. Flight plans for the G-1 and B200 flights were coordinated so that the G-1 transects were within the aerosol backscatter, extinction, and depolarization "curtains" simultaneously measured by the HSRL on the B200.

G-1 Instrumentation

Sampling of both activated and non-activated aerosols was carried out during the CHAPS through the use of two aerosol-sampling inlets on the G-1. Clear-air sampling was done through a Brechtel isokinetic inlet, which uses a two-stage diffuser assembly to decelerate the airflow. Although no attempt was made to separate the cloud droplets from the air stream coming into this inlet when the G-1 was in clouds, periods in which cloud drops entered the isokinetic inlet could be identified from the time series from the Condensation Particle Counter (CPC), which shows sudden, and very high, values during cloud passage.

A counterflow virtual impactor (CVI) inlet based on the design of Noone et al. (1988) was used for a second sampling line. This inlet uses a counter flowing air stream to selectively remove non-nucleated aerosols from the sampling flow. Small droplets (small than approximately 10 μm) are pushed out with the counter flow, while larger particles, including cloud droplets, pass through. The cloud droplets were then dried in a heated tube, leaving the aerosol kernel for analysis downstream. The CVI inlet used during the CHAPS was the same unit deployed by Hayden et al. (2008), who reported high levels of organics during ICARTT. They attributed these high levels to the siloxane sealent used on the tip of the CVI. Aware of this problem, extensive testing was conducted at the NOAA Earth System Research Laboratory to ensure that the results collected during the CHAPS would be free of this contamination.

The sampling streams from both inlets fed into essentially the same instrumentation for measuring the aerosol optical properties (Table 1), and each stream was sampled at reduced relative humidity (less than 40%). Aerosol absorption was measured using both a Radiance Particle Soot Absorption Photometer (PSAP) and a Droplet Measurement Technology (DMT) photo-acoustic soot spectrometer. Differences were found in the observations made by the PSAP and the photo-acoustic spectrometer. This may be related to the chemical composition of the aerosols as suggested by Subramanian et al. (2007), but the definitive cause of these differences is currently under investigation (e.g. Dubey and Mazzoleni 2008).

The AMS was able to sample from both inlet lines using a valve that allowed sampling from either stream (while flying with two AMS was considered, weight and space limitations precluded this option). This two-stream sampling necessitated making back-to-back flight legs in the cloud layer, one with the AMS sampling through the isokinetic inlet and a second leg immediately followed by another leg, with the AMS sampling through the CVI inlet. Details of the other instruments that sampled from the isokinetic inlet are described in Table 1, and included a DMT cloud condensation nuclei counter; a Fast Integrated Mobility Spectrometer (FIMS; Kulkarni and Wang 2006; Olfert et al. 2008); and Scanning Mobility Particle Sizer (SMPS). This suite of aerosol sizing instruments resulted in size spectra of aerosol diameter with a range of 16-444 nm. A Proton Transfer Reaction Mass Spectrometer (PTR-MS) provided continuous measurements of many gas-phase organic species, this sampling stream coming through yet a third inlet dedicated to gas-phase sampling that also included CO, SO_2, and O_3. While the relation of organic species and aerosols is part of the study, the gas phase measurements are also being used to define when the G-1 was within the Oklahoma City plume.

Separate from the inlet-sampling instruments noted above were a number of instruments mounted on external pylons of the G-1, including a DMT Passive Cavity Aerosol Spectrometer Probe (PCASP-100X) to measure the aerosol number density for aerosols between 0.17 and 3 μm diameter; a DMT Cloud, Aerosol, and Precipitation Spectrometer (CAPS) to measure the distribution of aerosols, cloud droplet, and rain droplet with diameters ranging from of 0.5 to 50 μm and of precipitation size particles between 25 and 1550 μm in diameter. A Gerber PVM-100A probe was used to measure the ambient liquid water content, and a Maycomm Inc. tunable diode laser hygrometer was used to measure the water content of the droplets sampled by the CVI.

The G-1 was also equipped with instruments to measure a number of meteorological parameters including three-dimensional turbulent winds, ambient temperature, water vapor, pressure, and upwelling and downwelling UV radiation.

One issue anticipated prior to the campaign was that the G-1 would be within small cumuli for very short time periods since the air speed of the G-1 is approximately 100 ms^{-1}. This was a concern because the response time of many of the instruments deployed on the G-1 was one second or more. This issue was highlighted by an earlier study by Berg and Kassianov (2008) who compiled a climatology of shallow clouds at the ACRF Central Facility for the summers of 2000 through 2004 using a cloud radar, lidar, ceilometer, and a radar wind profiler. They found that the distribution of cloud-chord lengths, defined as the cross-sectional length of the cloud that passes overhead, followed an exponential distribution, and that the average cloud-chord length was approximately 1 km. A similar analysis has been completed using data collected by the G-1, and concluded that the mean cloud-chord length sampled during CHAPS was 0.8 km, which is slightly less than is expected from the climatology. The distribution, however, was still well described by an exponential distribution (not shown). Two strategies are being used to address the sampling issue during analysis of the CHAPS data. First, statistics are only computed for periods in which the cloud chord length was greater than approximately 500 m. Second, a digital inversion method (Shaw et al. 1998) has been applied to nephelometer data collected with the CVI inlet. This method reconstruction the signal assuming that signal from the nephelometer behaves as a first order differential equation.

NASA King Air Instrumentation

The NASA Langley Research Center's King Air B200 was equipped with the NASA Langley High Spectral Resolution Lidar (HSRL). The HSRL technique takes advantage of the spectral distribution of the lidar return signal to discriminate aerosol and molecular signals and thereby measure aerosol extinction and backscatter independently at 532 nm. The Langley airborne HSRL also functions as a standard backscatter lidar at 1064 nm, enabling the calculation of the backscatter color ratio (β_{1064}/β_{532}). In addition, the lidar is polarization-sensitive at both wavelengths (i.e., it measures the degree to which the backscatter light is depolarized from the linear polarized state of the transmitted pulses), enabling discrimination between spherical and nonspherical particles. The major instrument parameters for the NASA Langley airborne HSRL instrument are shown in Table 2; Hair et al. (2006 and 2008) provide a much more complete description of this system and how it is used to measure profiles of aerosol backscattering, extinction, and depolarization.

CHAPS Surface Site

Surface observations were included in the CHAPS campaign in order to provide a baseline comparison for the aircraft data; these ground-based observations were continuous and closely paralleled many of the aerosol optical properties measured with the G-1. Both of the two ground sites were located north of Oklahoma City in order to increase the chance sampling would occur within the Oklahoma City plume during conditions with southerly winds. The location of each site and associated instruments are listed in Tables 3 and 4. Much of the instrumentation at the ground sites was similar to those deployed at the Atmospheric Radiation Measurement (ARM) Climate Research

Facility (ACRF) Southern Great Plains (SGP) Central Facility including a Micro Pulse lidar (MPL). This strategy was designed to facilitate a comparison of observations near Oklahoma City, with the background values more characteristic of the SGP site. Unfortunately, the large amounts of precipitation during CHAPS made it difficult to adequately dry the airstream sent to the nephelometer and PSAP, which complicates the analysis of scattering and absorption measurements made at the ASP surface site. A Total Sky Imager was deployed a few miles from the primary surface site. This instrument provided time-dependent hemispheric views of the sky, as well as estimates of cloud fraction and cloud aspect ratio. It was placed at a different location than the other instruments to allow for high-speed internet access with the imager.

The MPL at the CHAPS surface site was modified to include a pointing and scanning capability. This allowed the MPL to observe spatial differences in mixed layer development (by scanning in predetermined sequences) and provided a means by which observations of individual clouds and their immediate surroundings could be made. Using a real-time video camera mounted on the MPL's telescope allowed for measurements to be made around cloud edges resulting in the identification of several instances associated with well-defined inflow of aerosols into clouds. The 915 MHz Radar Wind Profiler (RWP) was configured to provide 30-min averaged wind profiles calculated from 30-s averaged spectra from beams pointed sequentially north, west, south and east, tilted 24° from vertical followed by a vertically pointed sample. Although not ideally configured for obtaining estimates of vertical velocity it was possible to combine data from the two instruments to make some preliminary findings that are described in the Preliminary Findings section.

Flight Patterns

Three basic flight patterns were used during the CHAPS (Figure 1). The first pattern consisted of straight and level flight legs flown at three altitudes including a low level flight at approximately 100 to 600 m below cloud base; two back-to-back legs through the cloud fields, with one leg having the AMS sampling through the isokinetic line and the second leg having the AMS sampling through the CVI line; and another leg flown at an altitude selected to be above the majority of clouds although, as would be expected from the characteristically wide range of cloud top heights associated with cumuliform clouds, there were a number of instances in which the G-1 intersected clouds during this highest leg.

Frequently, one vertical set of legs (below cloud/in-cloud/in-cloud/above cloud) was flown upwind of Oklahoma City, and two sets of legs were flown downwind of the city. This pattern let us sample the background air upwind of the city, as well as the more polluted conditions downwind. The second pattern was a ‘half-hexagon’ flown entirely downwind of the city (see Figure 1for the basis of this name). Regional air for this pattern was encountered as the hexagon wrapped around Oklahoma City, with the ends of these flight legs outside of the plume, as indicated by the CO concentration. These half-hexagonal patterns also had one leg below cloud base, two legs through the cumuli, and one leg above cloud top. This pattern was designed to increase the probability that the aircraft would intersect the Oklahoma City plume.

The third flight pattern was designed as part of a related experiment to make concurrent observations from the G-1 and King Air, in conjunction with observations made from aircraft concurrently in the field for the ARM Clouds and Land Surface Interaction Campaign (CLASIC) study. Both CHAPS and CLASIC were designed to investigate shallow cumuli. While CHAPS was focused on how clouds change the aerosol properties, CLASIC was designed to investigate the relationship to clouds and the processes at the surface. Five additional aircraft participated in CLASIC, including: the NASA ER-2, CIRPAS Twin Otter, Twin-Otter International, Duke Bell Helicopter, and the ARM Cessna 206. Details of the payloads carried by these aircraft can be found in Miller et al. (2009). Scientists associated with both CHAPS and CLASIC have a common interest in understanding observations made from the NASA Satellite A-Train and pooled their airborne resources in a coordinated pattern designed to relate in situ measurements with observations made by the A-Train. One flight plan involved making simultaneous, stacked measurements of aerosol extinction from each aircraft platform concurrent with the A-Train satellite overpass. This mission is discussed more fully in the Preliminary Results section.

We should note that many of the measurements made during CLASIC will augment the data collected during CHAPS and vice versa. The NASA ER-2 over flights included passes over the domain sampled by both the G-1 and the King Air. The MODIS Airborne Simulator was deployed on the ER-2, providing a high-resolution view of large areas of shallow clouds.

WEATHER CONDITIONS

June 2007 was the wettest June on record for much of Oklahoma. Approximately 33 cm of rain fell on central Oklahoma, which is nearly 20 cm more than normal (Oklahoma Climatological Survey, 2007). A persistent region of high pressure was located over the southeastern United States for most of June. The pressure gradient associated with this pattern led to generally southeasterly winds near the surface and significant low-level moisture advection from over the Gulf of Mexico. In addition to this low-level pattern, a number of slow moving upper-level lows contributed to the large amount of rainfall. The majority of the CHAPS flights were conducted during two periods, 6 through 12 June and 19 through 24 June, during which there was a weak ridge in the 500 mb pattern that led to some drying and an increase in the frequency of FWC.

PRELIMINARY RESULTS

Oklahoma City Plume

A central part of any data analysis will be to distinguishing regional air and air within the Oklahoma City plume. Evidence of the later was found on nearly every flight. An example showing observations of CO (strongly associated with urban emissions) collected during a sub-cloud leg on 23 June is shown in Figure 2. During this leg, CO values of approximately 110 ppbv were observed during the first part of a transect made below cloud base, downwind of Oklahoma City, with an abrupt increase highlighted by the shading in Figure 2. Concurrent with this abrupt increase in CO were increases in aerosol absorption and a decrease in the single scattering albedo (SSA). Together, these are the type of observations there were envisioned when designing the flight plans; the tails of the transect sampled aerosols in regional air, while the more central parts of each transect were made downwind of Oklahoma City and carried with them the associated aerosols emanating from within the city. The observed decrease in SSA is assumed to represent relatively fresh, ‘unprocessed’ atmospheric aerosols emanating from Oklahoma City. Support for this assumption comes from an examination of the aerosol size distribution as measured by the SMPS, FIMS, and PCASP, which indicate an order of magnitude more small particles (diameter less than 0.17 μm) in the Oklahoma City plume (Figure 3) than in the regional air, although negligible differences were measured in the number of particles greater than 0.4 μm. Relatively small aerosols scatter less light, leading to the increase in aerosol absorption with little change in the observed scattering. Some care must also be exercised when comparing the results from the FIMS and DMA to the PCASP because of different sampling conditions. The FIMS and DMA were located inside the G-1 and measure the dry aerosol size distribution, while the PCASP measures the aerosol size distributions at conditions closer to ambient. However, the PCASP was operated with de-icing heaters turned on causing some drying of the particles, so the sampling conditions of the PCASP were not truly ambient.

The small size of the aerosols on 23 June made it difficult to identify the Oklahoma City plume in the HSRL cross sections (Figure 4), and to determine the upwind and downwind legs from the aerosol scattering alone. Although an increase in scattering with height was observed by the HSRL this behavior was probably associated with the hygroscopic growth of the aerosols, a decrease in scattering shown by the arrow in Figure 5, is less easily explained, but could be related to a gradient in boundary-layer moisture (and hence a gradient in the hydroscopic growth), or a change in the underlying aerosol population. Data from the G-1 shows that there was a decrease in the total aerosol scattering near -97.6° (as indicated by the arrow in the figure), as well as a general decrease in relative humidity from east to west.

Evidence of cloud processing

A goal of the CHAPS was to identify aerosols that had under gone processing by clouds. Clear evidence of cloud samples within the urban plume was encountered during the flight of 11 June. On this day the cloud fraction measured by the G-1 was relatively low, at approximately 5% based on the fraction of time that the cloud-layer legs were inside clouds. The FWC that the G-1 encountered downwind of Oklahoma City showed well defined elevated levels of CO (Figure 6) with concentrations characteristic of the values measured below the clouds, indicating that the clouds are acting as conduits, transporting relatively dirty air up from the boundary layer to cloud top.

The efficiency with which aerosols are activated into cloud droplets is a key parameter of interest to modelers and others interested in relating aerosols to clouds. One way to evaluate the fraction of aerosols activated into droplets is to compare the total number of particles measured by the PCASP, which measures the aerosol size distribution for aerosol diameters between 0.17 to 3 μm, to the total number of particles that enter the CVI inlet measured by the CPC. Figure 7 shows the ratio of the PCASP total number to the total number of particles that enter the CVI inlet during one level flight leg. This ratio is approximately 1000 outside the clouds (as would be expected, indicating that very few dry aerosols enter the CVI inlet). In contrast, the ratio ranges from 10 to 1 inside the clouds. Although some of this change is associated with a reduction in the number of aerosols measured by the PCASP within some clouds, there is a large increase in the number of cloud droplets that enter the CVI inlet, and hence an increase in the number of particles measured with the CPC downstream of the CVI. This empirical measure of activation efficiency is certainly not perfect because some aerosols that had been too small to measure with the PCASP outside of the clouds will swell and move into the size range measured by the PCASP, thus inflating the numerator of this ratio.

The AMS provided a measure of the non-refractory composition of the aerosols that pass through the isokinetic or CVI inlets. Results from the same sets of transects made on June 11 are presented in Figure 8. On this day, the total aerosol mass decreases with height (not shown). Sulfate and organics dominate the mix of aerosols both upwind and downwind of Oklahoma City at all altitudes studied. However, the fractional amount of sulfate relative to the other components is smaller and the fractional amount of organics is larger downwind of Oklahoma City. This indicates that a large fraction of the aerosol mass produced in the vicinity of Oklahoma City is organic. There is also an increase in the mass fraction of nitrate within the cloud drops sampled by the CVI. The increase in nitrate mass is likely due to the uptake of nitric acid into the cloud drops and the subsequent neutralization of the nitrate by ammonia. The ratio of the ammonia to sulfate measured by the AMS provides some insight into the amount of ammonia, and its potential to neutralize both the sulfate and nitrate. A value of 2 indicates that the aerosols are of near neutral pH (e.g. Seinfeld 1986). The ratio was found to be less than 2 below clouds and slightly larger than two within the clouds, indicating that there was sufficient ammonia to produce the observed nitrate in the aerosol kernels.

A-Train Intercomparsion flights

There were a number of opportunities during CHAPS for intercomparison flights with the NASA A-Train satellites, with the results from one such comparison shown in Figure 9. This data, was taken on June 19 using the aircraft stacked pattern described earlier, and provides a comparison of measurements made from the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) system on Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO). The flight altitudes of the G-1, CIRPAS Twin Otter, and ARM Cessna 206 during the CALIPSO overflight are shown by arrows in the figure and the attenuated backscatter profiles from the CALIPSO lidar shown along with the corresponding profiles from the airborne HSRL.

During this flight over central Oklahoma and Kansas, considerable low-level broken clouds were observed and also detected by the HSRL and CALIPSO lidar measurements. In this example, the CALIPSO lidar vertical feature finder has identified broken clouds between 1 and 3 km and has identified an elevated aerosol layer near 4 km over Kansas. Figure 9 also shows relatively good agreement between the attenuated backscatter profiles averaged over this flight track from both lidar systems. We expect that data collected during the CHAPS and CLASIC missions will be useful for evaluating the aerosol and cloud measurements acquired by the CALIPSO lidar and other A Train sensors.

Surface Site

While data from the airborne instruments are very useful for evaluating in-cloud, out-of-cloud, below- and above-cloud differences, continuous observations from the CHAPs surface sites provide insight into the clouds and aerosols. One particularly useful measurement to come from the surface site are estimates of the inflow into shallow cumuli made from the MPL. One such case was observed on 22 June. In this case the MPL was held stationary for more than 3 hours (18:45-22:10 UTC) and pointed towards the southwest with an elevation angle of 30.7°. Near the surface, the winds were southerly at 7 ms^{-1}, and backed with height to southwestly at 10 ms^{-1} near 1.5 km above the surface. The geometry of the MPL and the wind speed resulted in clouds moving directly toward the MPL. The cloud-base height observed during this period rose slightly from 800 to 1000 m. Cloud tops, estimated from the topmost points of contiguous returns as the clouds moved through the MPL beam, were near 1.5 km (which corresponds to the height of the maximum wind speed).

The MPL returns for the period between 19:36 and 20:00 UTC are shown in Figure 10. These clouds are located at the top of boundary-layer thermals that have a base well within the mixed layer, as shown by the streaks of enhanced aerosol backscatter below the clouds. The streaks themselves are likely due to aerosols that are growing within the thermal as the relative humidity increases with height as the air rises in the boundary layer. The apparent tilt of the inflow and thermals is associated with the angle of the MPL from horizontal into the wind. If it is assumed that the plumes are perfectly vertical then the mean wind speed can be calculated from the difference in time indicated by the intersection of the top and bottom of the plume. Using typical values of height and time difference, gives an estimate of approximately 7 ms^{-1}, which agrees will with the wind speed observed by the radar wind profiler.

The instrument configuration at the ground site during CHAPS precluded simultaneous observations of the same cloud with the RWP and the MPL. However, Figure 11 shows individual estimates of vertical velocity (w) from the RWP during this period. Note that each estimate is representative only of 30 s time period, separated by 2.5 min; thus is it possible, even likely, that a direct measure of w during a single cloud passage above the RWP does not occur. Furthermore, the intersection of any given cloud base with the profiler beam will only occasionally capture a large portion of a given cloud. Observing the time series in Figure 11, several possible points for cloud inflow were chosen based solely on the maximum values of w. Figure 12 shows the vertical profiles of w and signal return for each of these times. All of the instances are associated with upward motion within the mixed layer, usually with maxima of 1.5-2 ms^{-1} at or below cloud base (as defined from Figure 10). The profiles at 18:54 and 19:16 have significant upward motion beginning as low as 200 m (the lowest range gate). Signal amplitudes at 18:54 display a maxima just below cloud base and again at or above cloud top; this points to relatively large amounts of turbulence associated with inflow and entrainment regions.

CONCLUSIONS

The summer 2007 CHAPS campaign was designed to collect observations relevant to a number of issues related to aerosols and clouds, including: differences in below-cloud aerosol optical and cloud nucleating properties downwind of Oklahoma City, the distribution of aerosol extinction in vicinity of shallow clouds, and differences in aerosol optical properties inside and outside of the Oklahoma City plume. Our first review of these observations suggest a rich data base suitable for analysis, including model studies related to the show activation of aerosols as they are lifted up from the convective boundary layer into the clouds, the chemical uptake of gaseous nitric acid, the transport of aerosols moving with the boundary-layer thermals into the shallow clouds, changes in the size distribution of aerosols upwind and downwind of Oklahoma City, and increases in aerosol absorption.

In addition to the primary research goals of the CHAPS, there was a unique opportunity to conduct some G-1 and King Air flights for validation of the NASA satellite A-Train. A successful satellite intercomparison flight, conducted in coordination with the CLASIC was completed and some results were presented. During this flight good agreement between the CALIPSO lidar and the HSRL was shown.

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Table 1. Instruments deployed on the G-1 aircraft during CHAPS.

Sampling Stream	Variable Measured	Instrument Name
Isokinetic and CVI		
	Aerosol absorption	Radiance Particle Soot Absorption Photometer (PSAP) and DMT Photo-acoustic Soot Spectrometer
	Aerosol scattering	TSI 3563 3-wavelength integrating nephelometer
	Aerosol number	TSI 3010 Condensation particle counter
	Aerosol composition	Aerodyne aerosol mass spectrometer
	Aerosol collection	Time-resolved aerosol collector (TRAC)
Isokinetic		
	Aerosol size distribution	Scanning Mobility Particle Sizer (SMPS) and Fast Integrated Mobility Spectrometer (FIMS)
	Cloud condensation nuclei	DMT dual-column cloud condensation nuclei counter
Chemistry		
	CO concentration	Vacuum UV
	O3 concentration	2B Ozone analyzer
	SO2 concentration	TEI 43S
	VOC concentration	Proton Transfer Reaction Mass Spectrometer (PTR-MS)
Aerosol, Clouds, and Precipitation		
	Size distributions of aerosols, cloud droplets, and precipitation	DMT Cloud, Aerosol, and Precipitation Spectrometer (CAPS)
	Aerosol size distribution	DMT Passive Cavity Aerosol Spectrometer Probe (PCASP-100X)
	Liquid water concentration	Gerber PVM-100A Probe, also Maycomm TDL hygrometer on CVI
Meteorological Variables		
	Turbulent winds	Gust probe
	Water vapor	TDL, General Eastern 1011B Chilled mirror
	Temperature	Platinum resistance thermometer
	Upwelling and downwelling UV radiation	Eppley Radiometer

Table 2. System parameters for the airborne HSRL

Transmitter	
Repetition Rate	200 Hz
532 nm energy	2.5 mJ
1064 nm energy	1 mJ
Optical Receiver	
Telescope	0.4 m diameter
532 etalon FWHM	40 pm
1064 IF FWHM	1 nm
Detection Electronics	
532 nm	PMT, analog detection
1064 nm	APD with analog detection

Table 3. Location of CHAPS surface sites

Site	Latitude (°N)	Longitude (°W)
Primary	36.605	-97.485
Secondary	35.6551	-97.4723

Table 4. Instruments deployed at the Primary and Secondary CHAPS surface sites

Variable Measured	Instrument Name
Aerosol Absorption	Radiance Particle Soot Absorption Photometer (PSAP)
Aerosol Scattering	TSI 3563 3-wavelength integrating nephelometer
Particle number concentration	TSI 3010 Condensation particle counter
Temperature/humidity	Vaisala Radiosonde system
Wind profiles	915 MHz wind profiler
Aerosol backscatter profile	Micro Pulse lidar

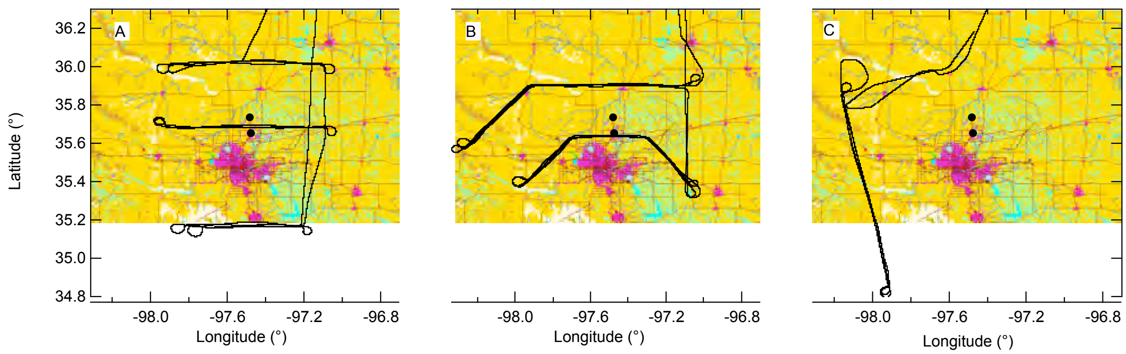

Figure 1. Represenative flight patterns flown by the G-1 during CHAPS, 20 June (A), 25 June (B), and 19 June (C). Colors indicate land use, with the magenta indicating Oklahoma City and other colors representing various, croplands, pastures, or forests.

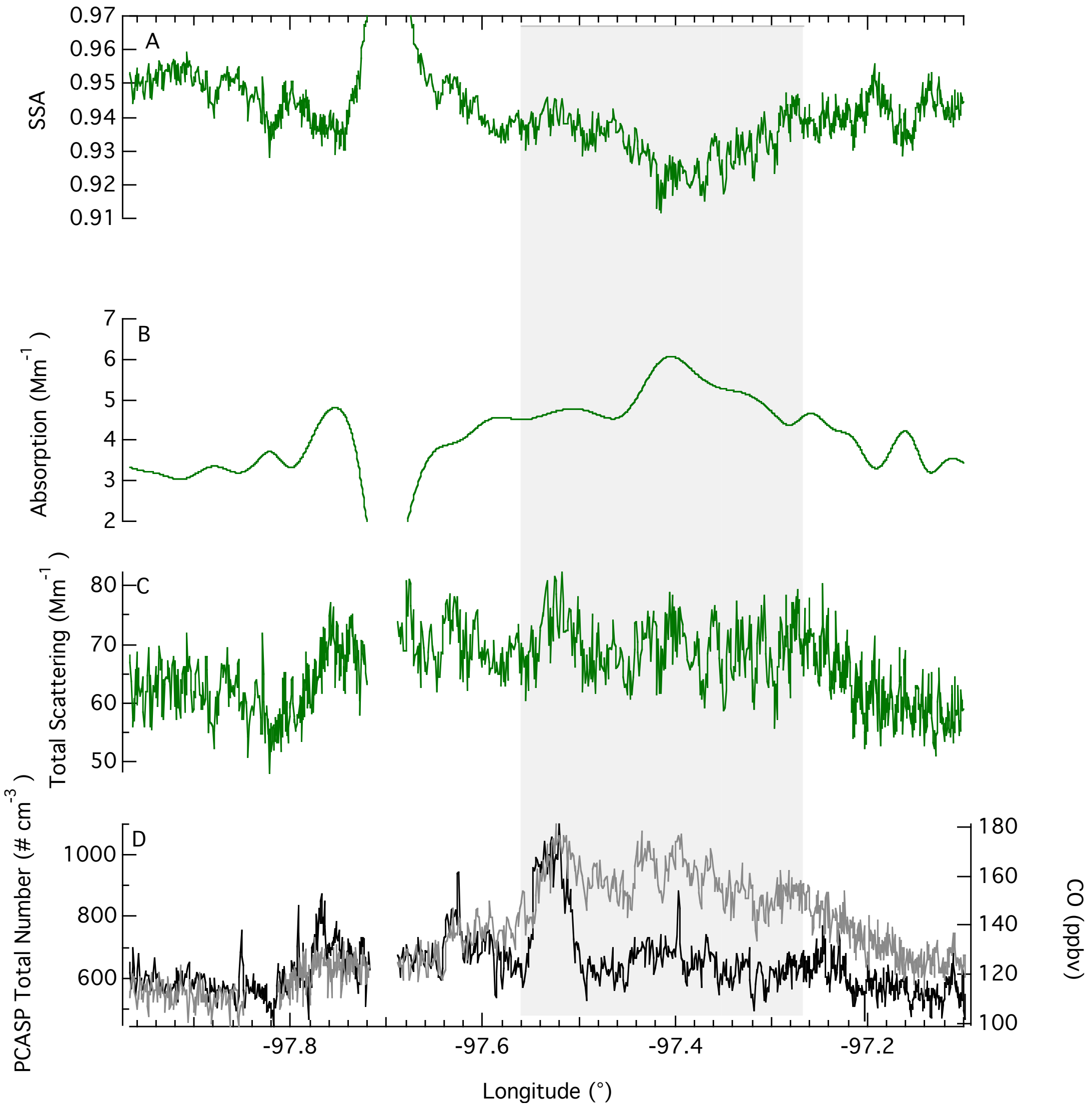

Figure 2. Time series of SSA at 550 nm (A), absorption at 550 nm (B), total scattering at 550 nm (C), PCASP total number concentration (black line) and CO concentration (grey line) (D) measured during a sub-cloud leg (~400 m above ground) on 23 June 2007 between 16:38 and 16:75 UTC. Shading indicates periods identified as being within the Oklahoma City plume.

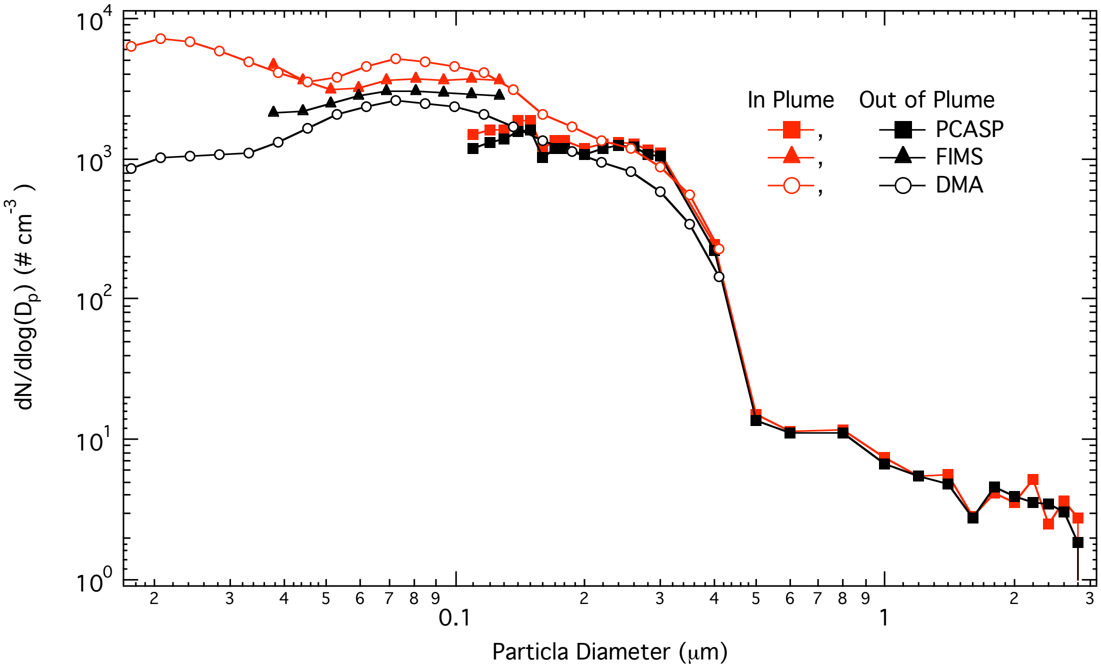

Figure 3. Aerosol size distributions inside (red) and outside (black) the Oklahoma City plume measured in a sub-cloud leg on 23 June 2007. Symbols indicate which instrument, FIMS (triangles), DMA (circles), or PCASP (squares) were used to measure the size distribution.

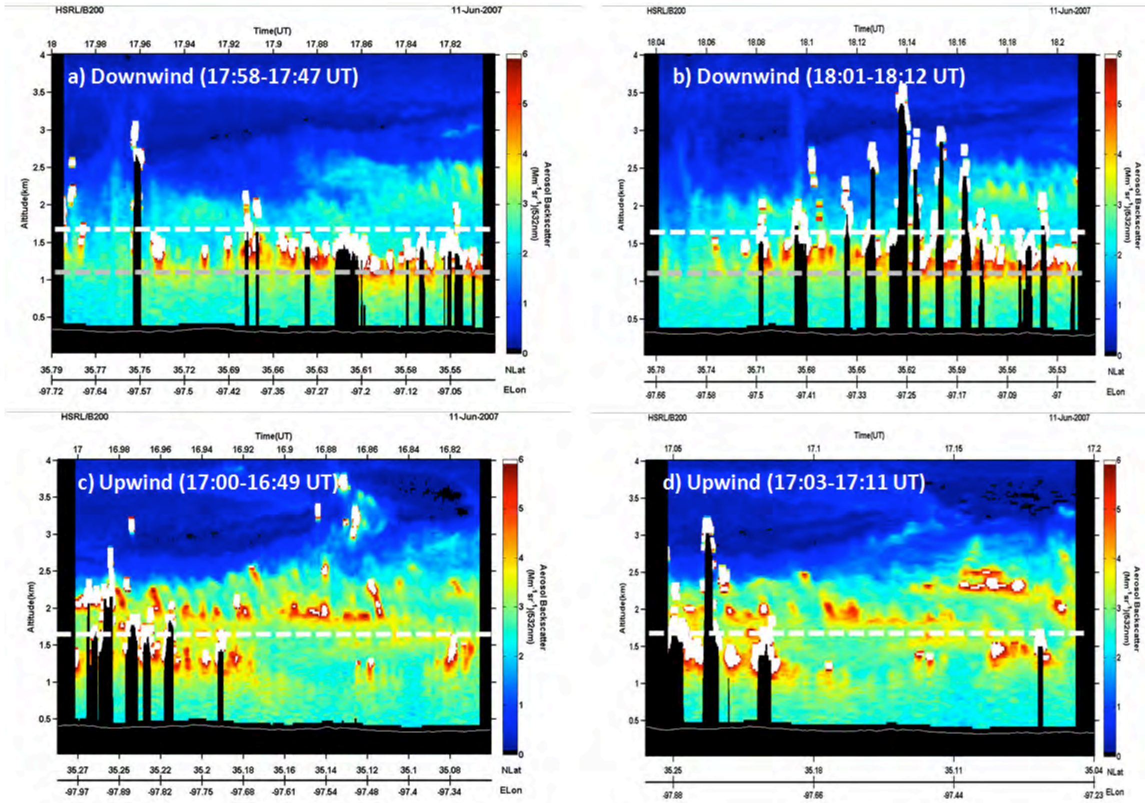

Figure 4. Aerosol backscatter profiles derived from HSRL measurements on June 11. a) and b) profiles measured downwind of OKC, c) and d) upwind of OKC. These measurements were coincident and colocated with the G-1 measurements shown in Figure 6. West (east) is on the left (right) side of these images. Time increases to the right for b) and d) and to the left for a) and c). The altitude of the G-1 legs through the cloud layer is shown by the dashed white lines, and the altitude of the G-1 during the downwind sub-cloud leg is shown by the dashed grey line.

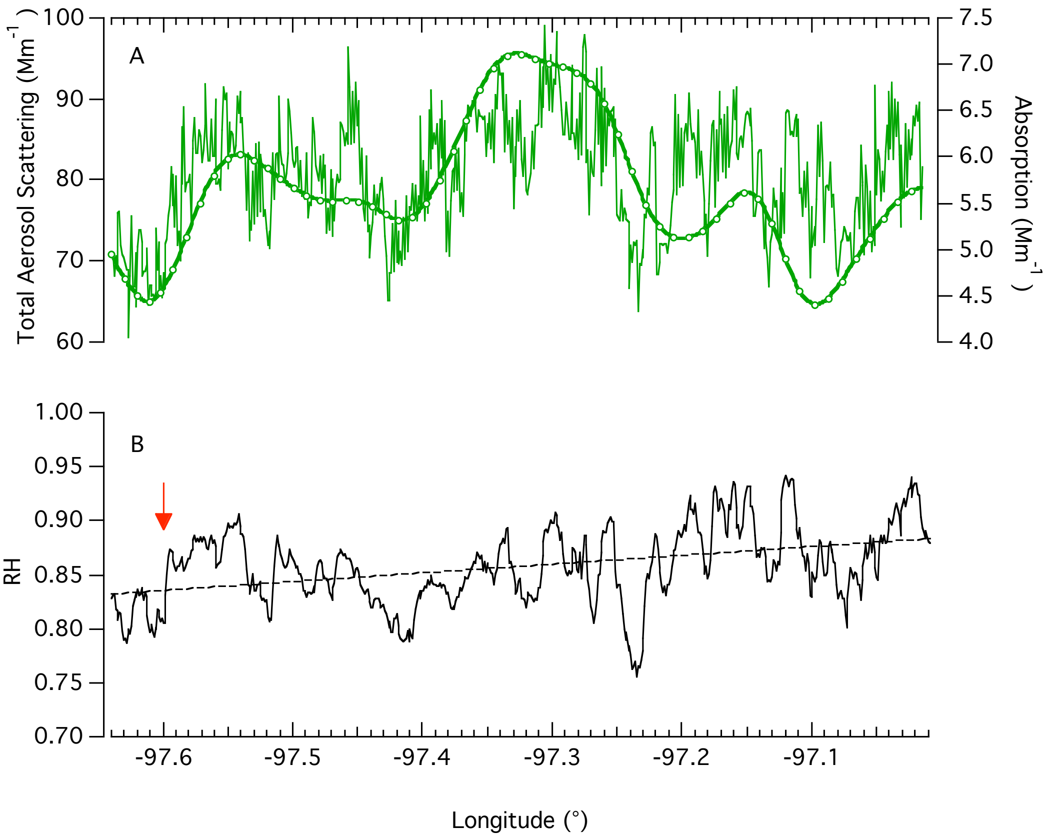

Figure 5. Plot of total aerosol scattering (solid line, left) and aerosol smoothed absorption (dashed line, right axis; A) and relative humidity (B) measured as a function of longitude by the G-1 for the sub-cloud leg flown on 11 June. The arrow indicates a marked decrease in the observed RH, and the dashed line is a least squares best fit to the relative humidity; see the text for details.

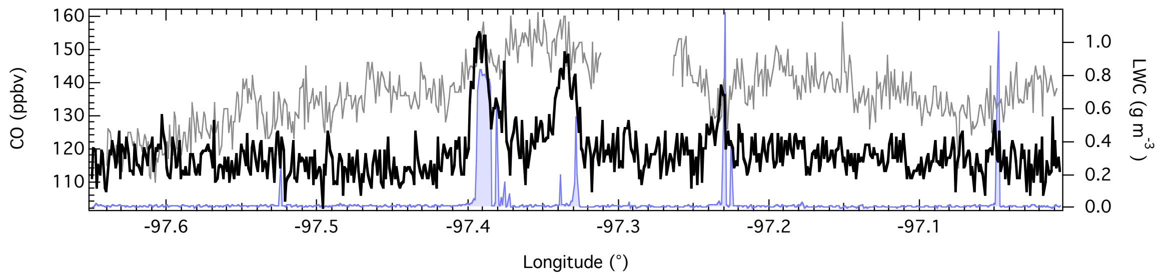

Figure 6. Below cloud (grey) and cloud layer (black) CO and LWC (blue) measured by the Gerber probe as a function of longitude on 11 June.

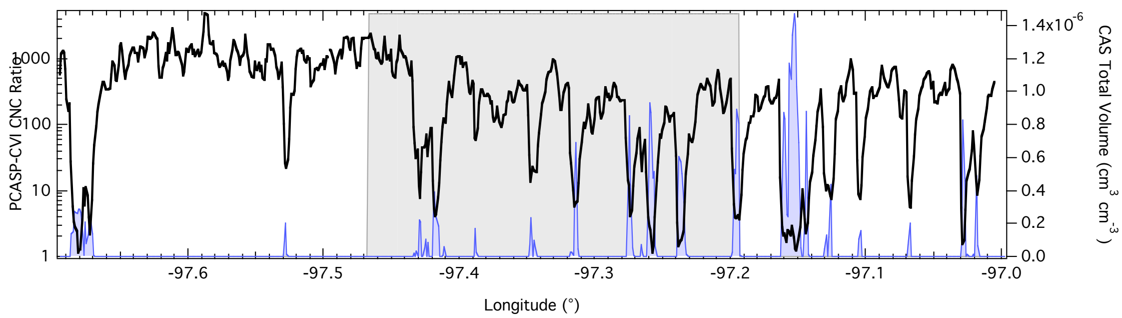

Figure 7. PCASP-CVI CNC ratio (black, left axis) and total volume measured by the CAS probe (blue) as a function of longitude on 11 June 2007. Shading shows the approximate extent of the sub-cloud plume.

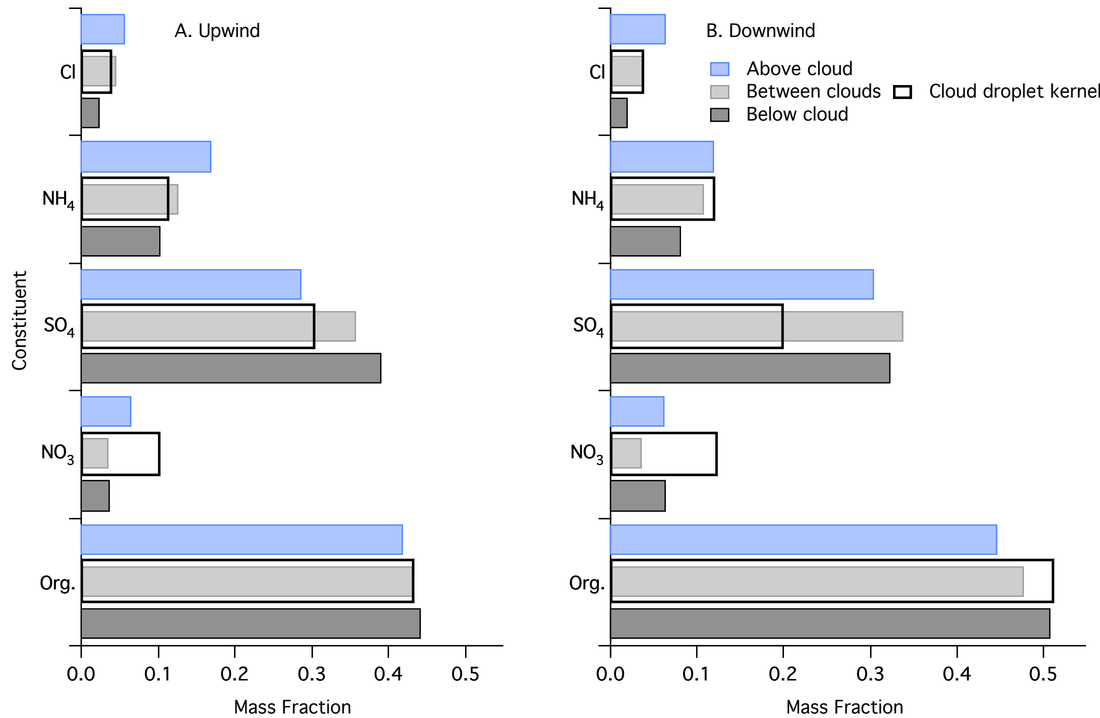

Figure 8. Mass fraction ~~fraction~~ of Cl, NH4, SO4, NO3, and organics observed on 11 June, 20007 ~~(green), NO3 (blue), SO4 (red), NH4 (purple), and Cl (orange)~~ upwind (A) and downwind of Oklahoma City (B). ~~below clouds (bottom), inside and outside of the clouds (middle), and above the cloud layer (top). Above cloud and cloud layer charts are for conditions downwind of Oklahoma City.~~Mass fractions observed in the subcloud layer are shown in black, mass fractions observed in the cloud layer are separated into cases outside of clouds (grey) and aerosol kernels of droplets that passed through the CVI (open black bar), and above the cloud (blue). The downwind aerosol kernels are for clouds associated with the Oklahoma City plume.

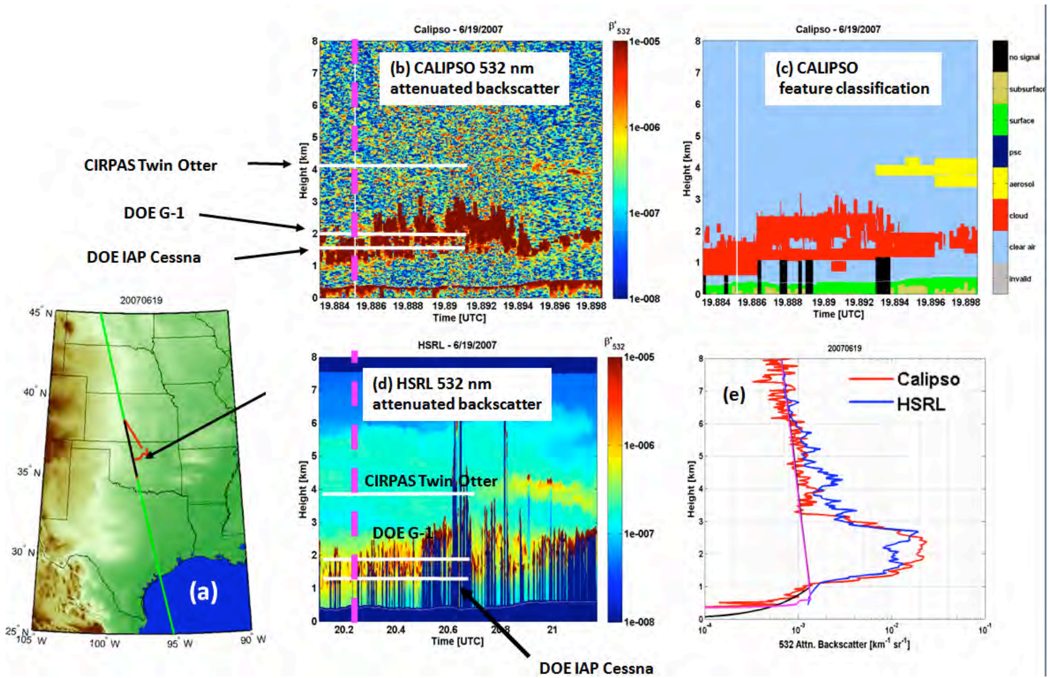

Figure 9. Map showing CALIPSO ground track (green), B200 flight track (red), and track of joint HSRL/CALIPSO lidar comparisons (black) (A); CALIPSO lidar attenuated backscatter profiles (km-sr)-1 (532 nm) (B). Each profile represents the running average of 15 0.33-km CALIPSO lidar profiles. The approximate altitudes of three other coordinated aircraft are also shown. The vertical purple line shows the exact coincidence time. Atmospheric feature classification as determined by the CALIPSO vertical feature finder (C), and same as (B) except for HSRL attenuated backscatter profiles (532 nm). Horizontal resolution is about 1 km (D). Comparison of CALIPSO lidar and HSRL attenuated backscatter profiles (532 nm) averaged over the track of joint lidar operations (E).

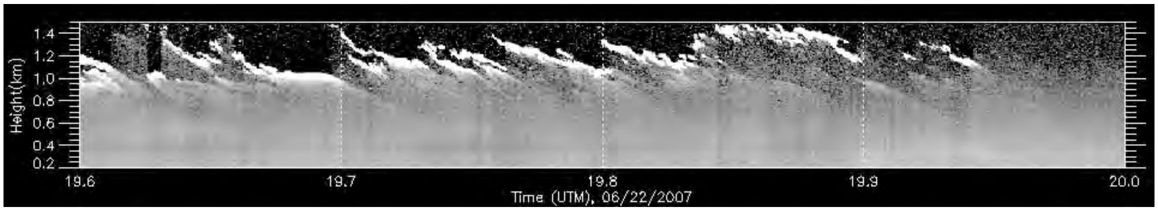

Figure 10. Range-corrected Micro Pulse Lidar returns from within the mixed and cloud layer above the surface site on June 22, 2007 during the CHAPS field study. The MPL was tilted at an elevation angle of 30 deg and azimuth of 207 deg. Data have been converted to height above the surface, thus returns from 1.5 km are about 2.6 km upwind.

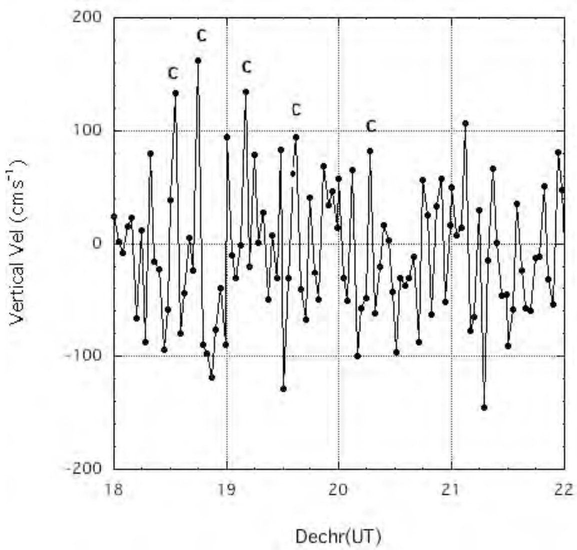

Figure 11. Time series of vertical velocities at 0.735 km AGL on June 24, 2007. Note that not contiguous; each value represents a 30 s average followed by roughly 2 min of no data. Chosen instances of possible cloud inflow are marked with the letter C.

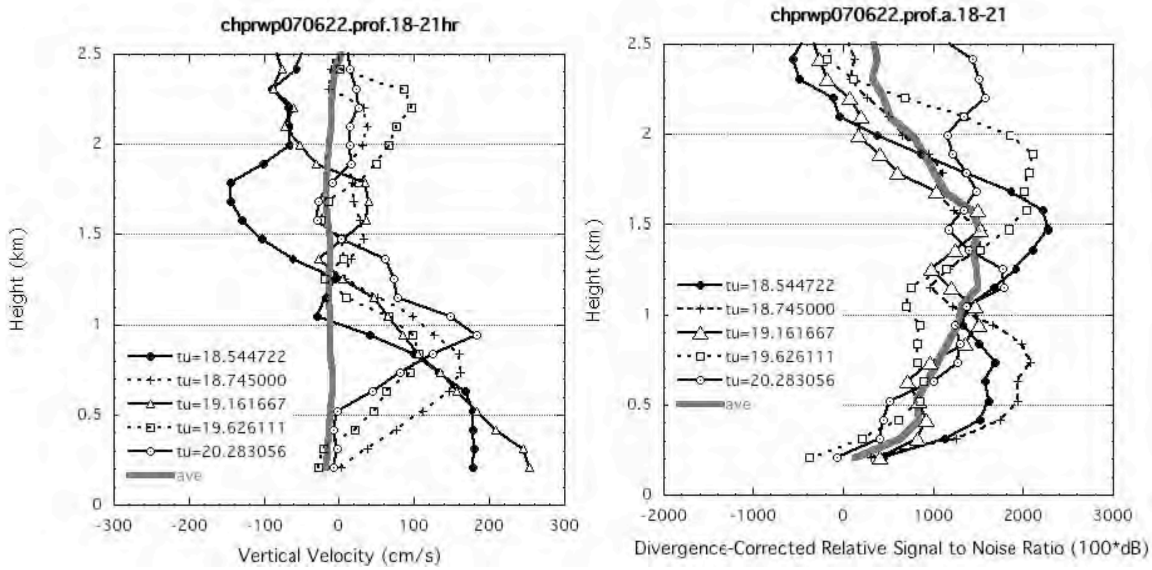

Figure 12. 30-s profiles of vertical velocity (left) and range-corrected signal amplitude (right) derived from RWP data, selected from likely periods where cloud inflow may have been captured.